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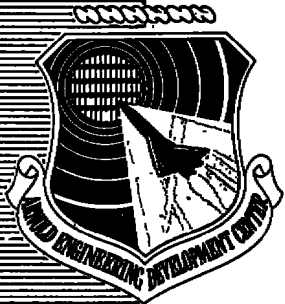
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TURBINE ENGINE FLOWPATH AVERAGING TECHNIQUES

T. W. Skiles
ARO, Inc.

October 1980

Final Report for Period January 1980 through October 1980

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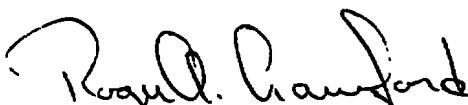
APPROVAL STATEMENT

This report has been reviewed and approved.

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FOR THE COMMANDER

ROGER A CRAWFORD, Lt Col, USAF
Assistant Deputy for Propulsion Test
Deputy for Operations

SUMMARY

Methods of determining the one-dimensional or mean value of a measured flow property for gas turbine engines were investigated. The investigation consisted of a literature review and review of turbine engine current flowpath averaging practices. The two basic methods for determining the mean value of a measured flow property for turbine engines are area and mass weighting. The two methods are compared and recommendations for additional flowpath averaging investigations are offered.

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NOMENCLATURE

A	Area
CD	Convergent-divergent
FAR	Fuel-air ratio
FHV	Fuel heating value
FN	Engine net thrust
H	Total enthalpy
HAE	Augmentor exit total enthalpy
HC	Engine core total enthalpy
HD	By-pass duct total enthalpy
HFA	Augmentor fuel enthalpy
HPC	High-pressure compressor
HPT	High-pressure turbine
LPC	Low-pressure compressor
LPT	Low-pressure turbine
$\dot{m}$	Mass flow function, $\dfrac{W \times \sqrt{T}}{PS \times A}$
n	Number of individual areas
P	Total pressure
PS	Static pressure
R	Radius; gas constant
SFC	Specific fuel consumption
SLS	Sea-level-static
T	Total temperature
VAE	Augmentor exit velocity
W	Mass flow rate
WAC	Engine core mass flow rate

WAD	By-pass duct mass flow rate
WAE	Augmentor exit gas flow rate
WAT	Augmentor total mass flow rate
WAI	Augmentor inlet gas flow rate
WFA	Augmentor fuel flow

Subscripts

A	Augmentor
AREA AVG	Average value calculated by area weighted method
AVG, AV	Average value
CALC	Calculated value
DELTA	One percent change in averaged measured parameter
HUB	Compressor hub radius
i	Individual value
loc	Local
MASS AVG	Average value calculated by mass weighted method
MAX	Maximum value
meas	Measured value
MIN	Minimum value
NOMINAL	Nominal value
PROBE	Value of individual probe on measurement rake
REF	Reference value
TIP	Compressor tip radius
TOTAL	Total value

GREEK SYMBOLS

γ	Ratio of specific heats
ΔP	Change in total pressure
η	Efficiency

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INTRODUCTION

The gas turbine engine is composed of different components arranged in series and/or parallel and is amenable to one-dimensional flow analysis. Each engine component exerts changes on the gas as it flows through the engine creating changes in the flow properties. The changes exerted on the gas by each engine component must be known in order to determine performance of engine components and engine systems. Engine performance is typically determined using analysis based on averaged measured values and mean calculated properties with the assumption of one-dimensional flow applied to the turbine engine flow processes (Ref. 1) even though fluid properties vary with engine axial, radial, and circumferential position. Equations based on one-dimensional flow do not precisely describe the fluid motion but has been found to be a good approximation for overall engine component performance (Ref. 2). Furthermore, the assumption of one-dimensional flow greatly simplifies the basic equations, data reduction computer programs, and mathematical simulations. The information required for performance determination is usually obtained at the inlet and exit planes of the various engine components of the engine system.

The investigation reported herein was sponsored by AEDC/DOP and conducted under Program Element 65807F. The investigation was conducted under ARO Project No. E43Y-14.

No common flowpath averaging technique of measured parameters currently exists among turbine engine development test centers. Identification and evaluation of different flow averaging capabilities is needed to determine differences in component and engine performance, increase fidelity of component and engine simulation and provide a basis for comparison of data from the various test facilities.

The specific objectives of this evaluation were to identify existing engine flowpath averaging practices and numerically compare some of the more common flowpath averaging techniques.

FLOWPATH AVERAGING PRACTICES

LITERATURE REVIEW

Several investigations of flowpath averaging techniques have been accomplished previously for different classes of flow. However, no previous investigation has directly addressed engine system averaging techniques. Tyler (Ref. 3) presented a method of determining "suitable mean values" of flow parameters to be used when one-dimensional flow methods are applied to a circular duct in which a boundary layer exists.

Wyatt (Ref. 4) developed a method of defining a uniform flow by equating the mass flow and momentum of the uniform flow to the mass flow and momentum of the real flow in a constant-area duct without wall friction. In addition, Wyatt numerically investigated conventional averaging methods by considering several

velocity gradients confined to subsonic compressible flow with constant static pressure and total temperature. Comparison of conventional averaging methods and the mass-momentum method developed during Wyatt's investigation concluded that conventional averaging methods can cause errors in calculated uniform flow properties while uniform flow properties determined from the mass-momentum method are without error.

Livesey (Refs. 5 and 6) developed a method of determining mean values of flow parameters based on the equivalence of a uniform flow and a nonuniform flow utilizing enthalpy flux, entropy flux and mass flow rate. Livesey's development results in a set of mean flow property definitions including velocity, density, static and total temperature, and total pressure.

Traupel (Ref. 7) and Dzung (Ref. 8) have each developed a method of flow parameter determination based on the solution of physical and thermodynamic relations. Traupel utilizes the definitions of flow velocity, temperature based on the enthalpy definition, entropy, and pressure as a function of enthalpy and entropy to determine average flow parameters. Dzung utilizes the conservation equations of continuity, moment of momentum, momentum, and energy and a basic relation of enthalpy as a function of temperature, pressure and density to determine average flow parameters.

Decher (Ref. 9) investigated the roles of mass averaged total temperature, total pressure, and exit static pressure nonuniform profiles on nozzle performance. During this investigation, Decher developed equations for the equivalent mass averaged total pressure and total temperature of nozzle flow based on the conservation of mass and total enthalpy by considering nozzle flow to consist of a large number of noninteracting stream tubes. Results indicate mass averaged temperatures and pressures and nozzle performance are influenced by nonuniform profiles of temperature and pressure.

Kuchar (Ref. 10) analytically investigated several methods of averaging total pressure and temperature profiles at the entrance to jet engine exhaust nozzles using a concept of conservation of ideal available thrust. Results indicate that, for best agreement with uniform nozzle coefficients, pressure profiles should be mass weighted and temperature profiles should be "thrust" weighted for analyzing nozzle performance.

CURRENT FLOWPATH AVERAGING PRACTICES

Instrumentation is an important consideration in selecting a flowpath averaging technique. Inlet and exit pressures and temperatures are usually measured at engine component interfaces or measurement stations (Fig. 1) using fixed rakes spaced in circumferential locations. The number of measurements made at

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each station can vary depending on the objectives of the test under consideration. Wall static pressures can be located in a circumferential position at the component inlet and exit stations. The general practice for pressure and temperature rakes is to locate measurement probes on centers of equal area.

Information on engine flowpath averaging practices were obtained (Refs. 11 through 13) from the following test establishments:

Arnold Engineering Development Center (AEDC)

National Aeronautics and Space Administration – Lewis Research Center (NASA-Lewis)

National Gas Turbine Establishment (NGTE)

Centre d'Essais des Propulseurs (CEPr)

Flowpath averaging techniques of the major testing establishments include various methods of parameter averaging. Current practices of each of the contributing test establishments are presented in Table 1. The determination of a mean value, in general, falls into three categories: (1) some form of direct numerical averaging of measured flowpath properties, (2) energy or work balances across a component or engine system, and (3) solution of a system of conservation equations such as the DZUNG average (Ref. 8). A conclusion of current practices is that in defining a method of determining the mean value of a measured flow property, two basic methods stand out. These are area weighted and mass weighted methods. Combinations of both are used to evaluate engine performance parameters. Measured pressures and temperatures used to compute engine system performance are usually area averaged, although, mass averaged values are also used. Calculation of engine system performance requires thermodynamic flow properties (Ref. 14) in addition to pressures and temperatures. References 15 through 22 describe some of the experimental and flowpath averaging practices used in component and engine system performance testing.

COMPARISON OF FLOWPATH AVERAGING TECHNIQUES

An averaged parameter obtained by the area-weighted method is calculated by a summation of each individual measured parameter multiplied by the individual cross-sectional area corresponding to the individual measured parameter and divided by the total cross-sectional area.

$$P_{AREA\ AVG} = \frac{\Sigma\ P_i A_i}{A_{TOTAL}} \quad ; \quad T_{AREA\ AVG} = \frac{\Sigma\ T_i A_i}{A_{TOTAL}}$$

To mass average test data, a local static flow property, usually static pressure, is required. The general practice is to assume the radial static pressure is constant. An averaged parameter obtained by the mass-weighted method is calculated by an iterative solution of the following equations:

$$P_{MASS\ AVG} = \frac{\frac{1}{n} \Sigma\ P_i\ \frac{\dot{m}_i}{\sqrt{T_i}}}{\frac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}} \quad ; \quad T_{MASS\ AVG} = \frac{\frac{1}{n} \Sigma\ \dot{m}_i\ \sqrt{T_i}}{\frac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}}$$

$$\text{and}\quad W_{TOTAL_{meas}} = \frac{\dot{m}\ x\ PS\ x\ A_{TOTAL}}{\sqrt{T_{MASS\ AVG}}}$$

The mass-weighted method utilizes individual measured total pressures and total temperatures and measured total airflow (see Appendix).

Comparison of the basic flow averaging methods was accomplished using a baseline compressor distortion pattern generated from the measured parameters of total pressure and total temperature presented in Fig. 2. Data for the baseline compressor distortion patterns were obtained during sea-level-static (SLS) testing of a state-of-the-art turbofan engine at a corrected rotor speed of approximately 87 percent at the AEDC. The parameters were measured with fixed rakes with five measurement probes located on centers of equal area. Total pressure distribution (isobars) and total temperature distribution (isotherms) at the inlet and exit of the representative low bypass turbofan HPC are presented in Figs. 3 and 4. The total pressure and total temperature values are normalized by the integrated area averaged values of pressure and temperature, respectively.

Circumferential total pressure and total temperature profiles at the inlet and exit of the HPC comparing the basic averaging methods are presented in Fig. 5. Total pressure and total temperature values were obtained from the baseline distortion patterns by superimposing a five-probe rake at each successive circumferential location. Averaged values of total pressure and total temperature were obtained using the two basic averaging methods; area and mass averaging. The averaged values were referred to an area integrated value obtained from the baseline distortion patterns. Figure 5 indicates that for the patterns presented in Figs. 3 and 4 the averaged value can deviate from the area integrated value as much as 1.3 percent because of circumferential location of measurement points and the difference

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in area and mass averaging methods can be as much as 0.5 percent. The severity of the distortion patterns will change through the compressor as a result of geometry, blade loading and crossflow (Ref. 23).

The circumferential profiles presented in Fig. 5 were obtained at a corrected rotor speed of approximately 87 percent. The basic distortion pattern does not change appreciably as engine power is changed; however, the amplitude of the distortion level does change.

Total pressure and total temperature distortion index at the inlet and exit of the representative HPC as a funtion of corrected rotor speed is presented in Fig. 6. A distortion index was defined as the absolute maximum value minus the absolute minimum value divided by the face area average value. This definition yields the maximum value of distortion index because the entire distortion pattern is utilized in determining the maximum and minimum values. The total pressure and total temperature distortion is normalized by the area averaged values of pressure and temperature, respectively. However, no discernible difference is noticed by using the mass averaged or area averaged values of pressure and temperature in the calculation of the distortion index. The differrence between the area averaged value and mass averaged value at each circumferential location would be expected to change as distortion level changes with the power level.

Averaged values of total pressure and total temperature were obtained for the entire measurement station and comparisons of the basic averaging methods as a function of corrected rotor speed are presented in Fig. 7. The difference between mass averaged and area averaged values of total pressure and total temperature is a maximum of 0.6 percent for the instrument configuration utilized. The area averaged total pressure and total temperature values are, in general, greater than the mass averaged total pressure and total temperature at the inlet with no observable trend at the exit.

PERFORMANCE CHANGE AND MEASUREMENT UNCERTAINTY

All measurements have measurement errors. These errors are the differences between the measurements and the true value. Measurement uncertainty is defined as the maximum error which might reasonably be expected and is a measure of the closeness of the measurement to the true value. Uncertainty assessment consists of an audit of the random (Precision) and fixed (Bias) errors which result from the measurement of a value. The method of Ref. 24 was followed in the evaluation of measurement uncertainties. Measurement uncertainty for a single measurement is defined as

$$\pm U = \pm (B = t_{95} \, S)$$

where B is the upper limit of the bias error from the true value, S is the precision error which is an estimate of the true standard deviation of repeated values of the measurement, and t_{95} is the student-t statistical parameter at the 95 percent confidence level. The bias and precision errors utilized for the evaluation of uncertainty values were obtained during testing of a state-of-the art turbofan engine at AEDC.

Flowpath averaged parameters are not single measurements but are determined as a function of several individual measurements. To assess the measurement uncertainty of flowpath averaged parameters, it is necessary to propogate individual measurement uncertainties through a function that relates the flowpath averaged parameters and the individual measurements. The error propagation is approximated with a first order Taylor's series method. Measurement uncertainties were obtained for the mass averaged and area averaged methods utilizing the same bias and precision errors. The measurement uncertainty for the mass averaged method is greater than the measurement uncertainty for the area averaged method. Uncertainty results, in terms of absolute values, are presented in Table 2.

When dealing with gas turbine engines, it is desirable to know how engine performance changes with variation of parameters used to calculate engine performance. These parameters include averaged values of total pressure and temperature at measurement stations. Changes of engine performance due to variations of averaged total pressure and temperature was determined by the application of a digital computer program simulation (Ref. 25) to a current engine system. Nominal engine performance was obtained by application of the computer simulation utilizing data obtained during SLS testing at the AEDC. Total pressure and temperature were independently varied one percent above and below the nominal value at the engine inlet, HPC inlet, and HPC exit and engine performance obtained. Engine performance changes due to a one percent variation of total pressure and temperature at the representative measurement stations are presented in Table 3 in terms of percent change.

CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this evaluation was to investigate the methods for determining the one-dimensional or mean value of a measured flow property. Specific efforts were a literature review of previous investigations and current flowpath averaging practices and a numerical comparison of fundamental flowpath averaging techniques. The following conclusions have been drawn from these efforts:

1. Several investigations of flowpath averaging techniques for different classes of flow have been reported in the literature but the subject of turbine engine flowpath

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averaging of measured flow properties has not been reported.

2. Measurements are usually made at measurement stations using fixed rakes with probes located on centers of equal cross-sectional areas. The number and location of instrumentation measurements can have a large influence on the value of an average flow property.

3. Current practices of gas turbine engine development and test centers show that, in general, area weighted and mass weighted types of flowpath averaging are performed for engine system testing.

4. The mass weighted method of flowpath averaging was within 0.5 percent of the area weighted method for the average total pressure and within 0.6 percent of the area weighted method for the average total temperature for the instrument configuration and power levels investigated.

5. Uncertainty calculations for mass averaging and area averaging methods indicate mass averaging methods can increase the uncertainty level of the averaged flow properties indicating a need for uncertainty evaluations to be included in the selection process of an averaging method.

6. Utilizing a current digital computer program simulation, a one percent variation of measurement station total pressure and temperature at the conditions investigated results in engine performance changes of one percent or less.

Additional areas of averaged flow property determination which require consideration are:

1. Boundary layer effects: The change in the value of an averaged parameter considering the effects of boundary layer should be investigated.

2. Balancing techniques: Energy and work balances are currently used in determination of measurement station average properties. An effort should be made to compare differences between mass and area averaging type calculations and balancing calculations.

3. Systems of equations: Investigation of the determination of mean values of a flowpath property by simultaneous solution of conservation and state equations should be made and compared to mass and area averaging type calculations.

4. Performance variation: Engine performance variations due
    to variations of averaged parameters should be
    investigated utilizing a mathematical simulation such as
    the parallel compressor theory.

5. Additional components: Flowpath averaging methods
    utilizing distortion patterns of components such as
    combustors, turbines, and nozzles need to be
    investigated.

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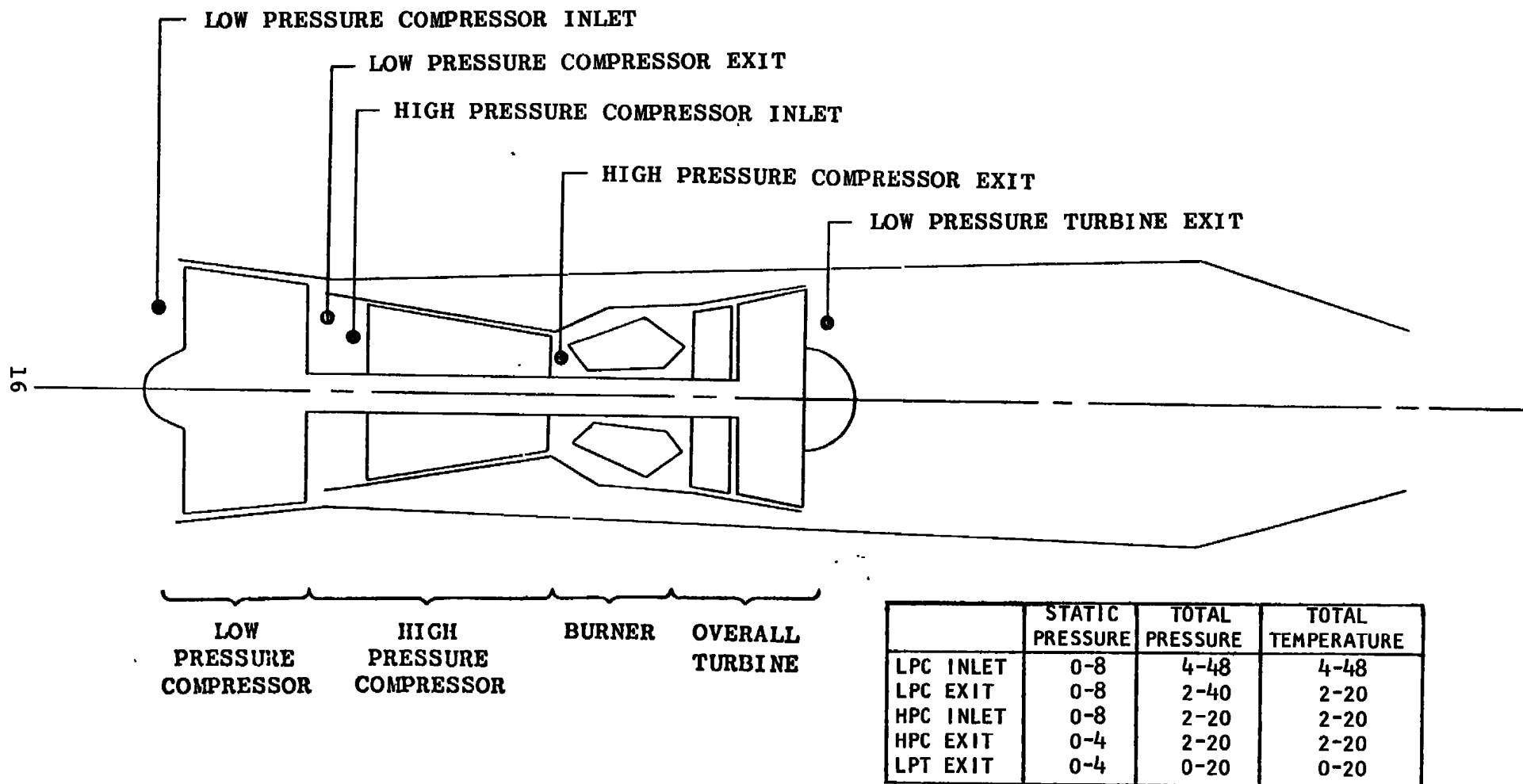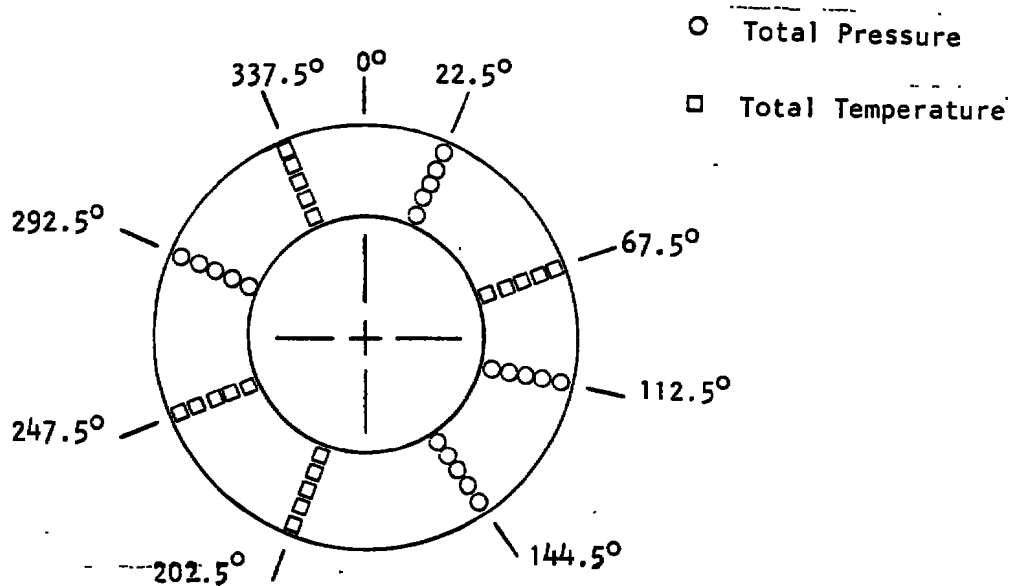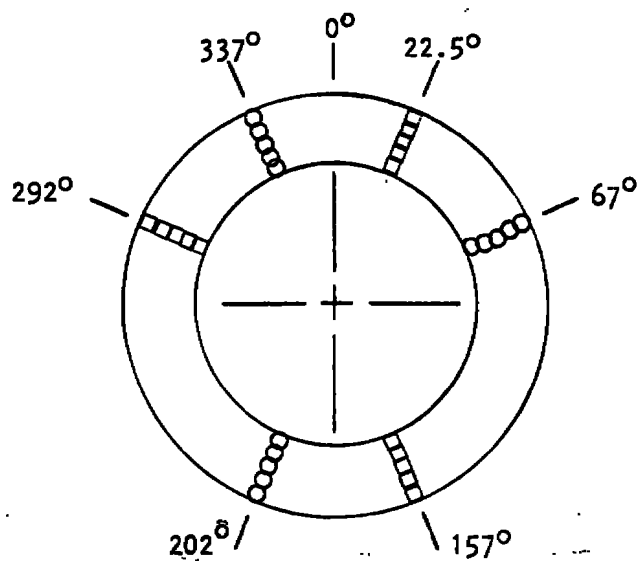25. McKinney, John S., Capt, USAF. "Simulation of Turbofan Engine." AFAPL-TR-67-125, November 1967.

LOW PRESSURE COMPRESSOR INLET

LOW PRESSURE COMPRESSOR EXIT

HIGH PRESSURE COMPRESSOR INLET

HIGH PRESSURE COMPRESSOR EXIT

LOW PRESSURE TURBINE EXIT

LOW PRESSURE COMPRESSOR	HIGH PRESSURE COMPRESSOR	BURNER	OVERALL TURBINE

	STATIC PRESSURE	TOTAL PRESSURE	TOTAL TEMPERATURE
LPC INLET	0-8	4-48	4-48
LPC EXIT	0-8	2-40	2-20
HPC INLET	0-8	2-20	2-20
HPC EXIT	0-4	2-20	2-20
LPT EXIT	0-4	0-20	0-20

Figure 1. Representative Engine System Measurement Stations and Number of Parameters Measured

O   Total Pressure

□   Total Temperature

337.5°   0°   22.5°

292.5°

67.5°

112.5°

247.5°

202.5°

144.5°

a. HIGH PRESSURE COMPRESSOR INLET

337°   0°   22.5°

292°

67°

202°

157°

b. HIGH PRESSURE COMPRESSOR EXIT

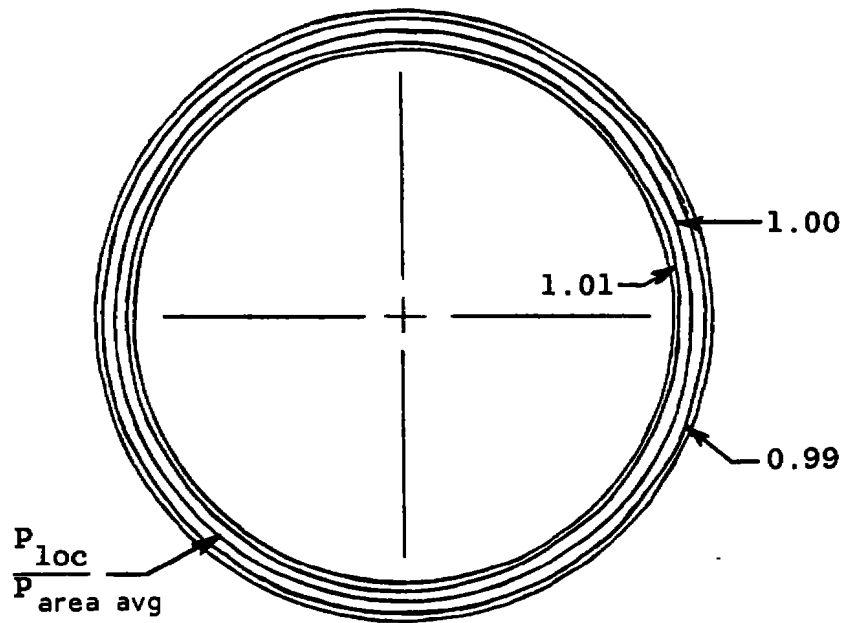Figure 2.   Schematic of Compressor Instrumentation Used for
Flow Averaging Evaluation
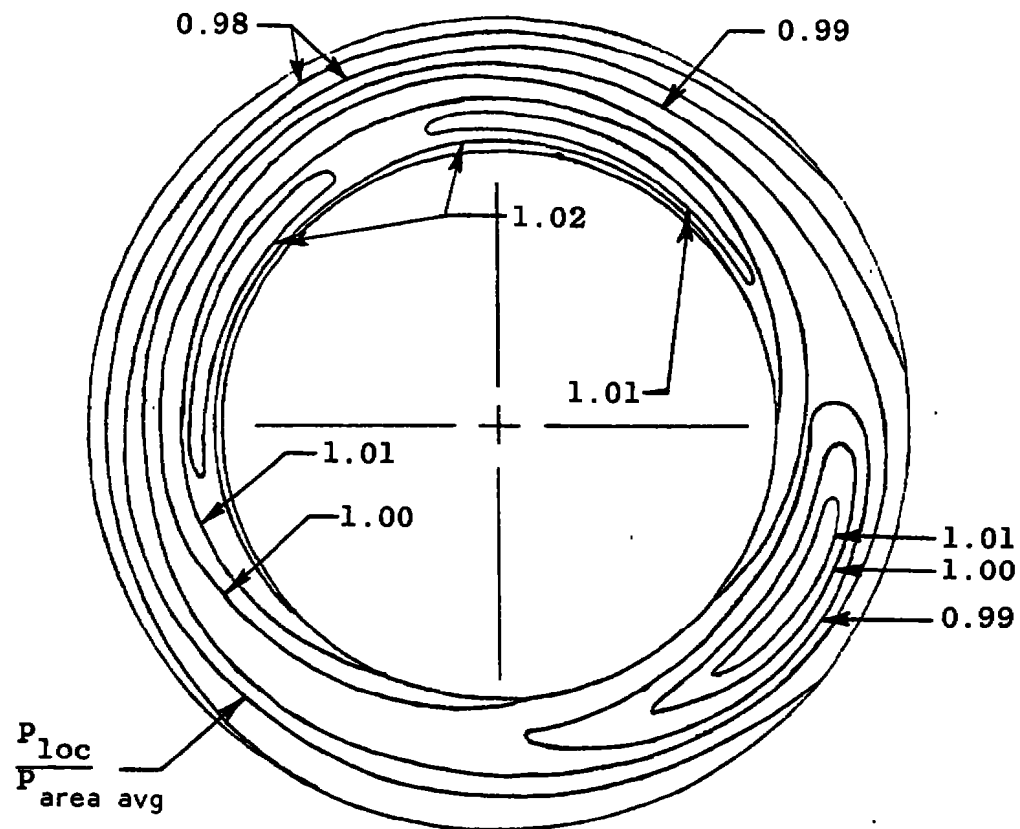
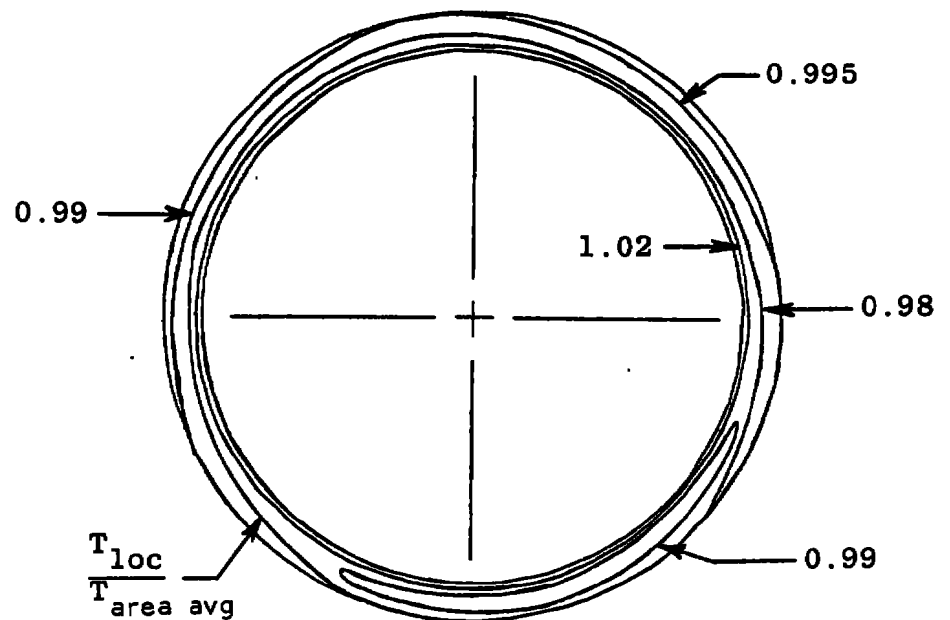a. Total Pressure Distribution (Isobars)
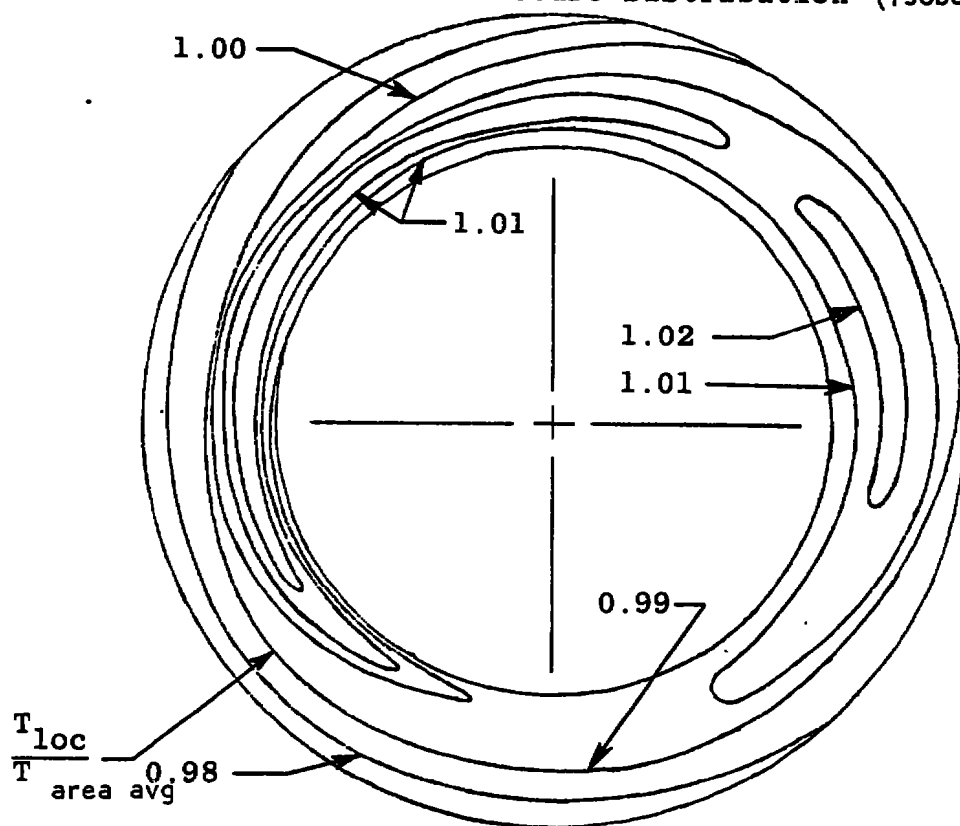
b. Total Temperature Distribution (Isotherms)

Figure 3.   Baseline Compressor Inlet Distortion Pattern for
Flow Averaging Evaluation

a. Total Pressure Distribution (Isobars)

b. Total Temperature Distribution (Isotherms)

Figure 4.   Baseline Compressor Exit Distortion Pattern for
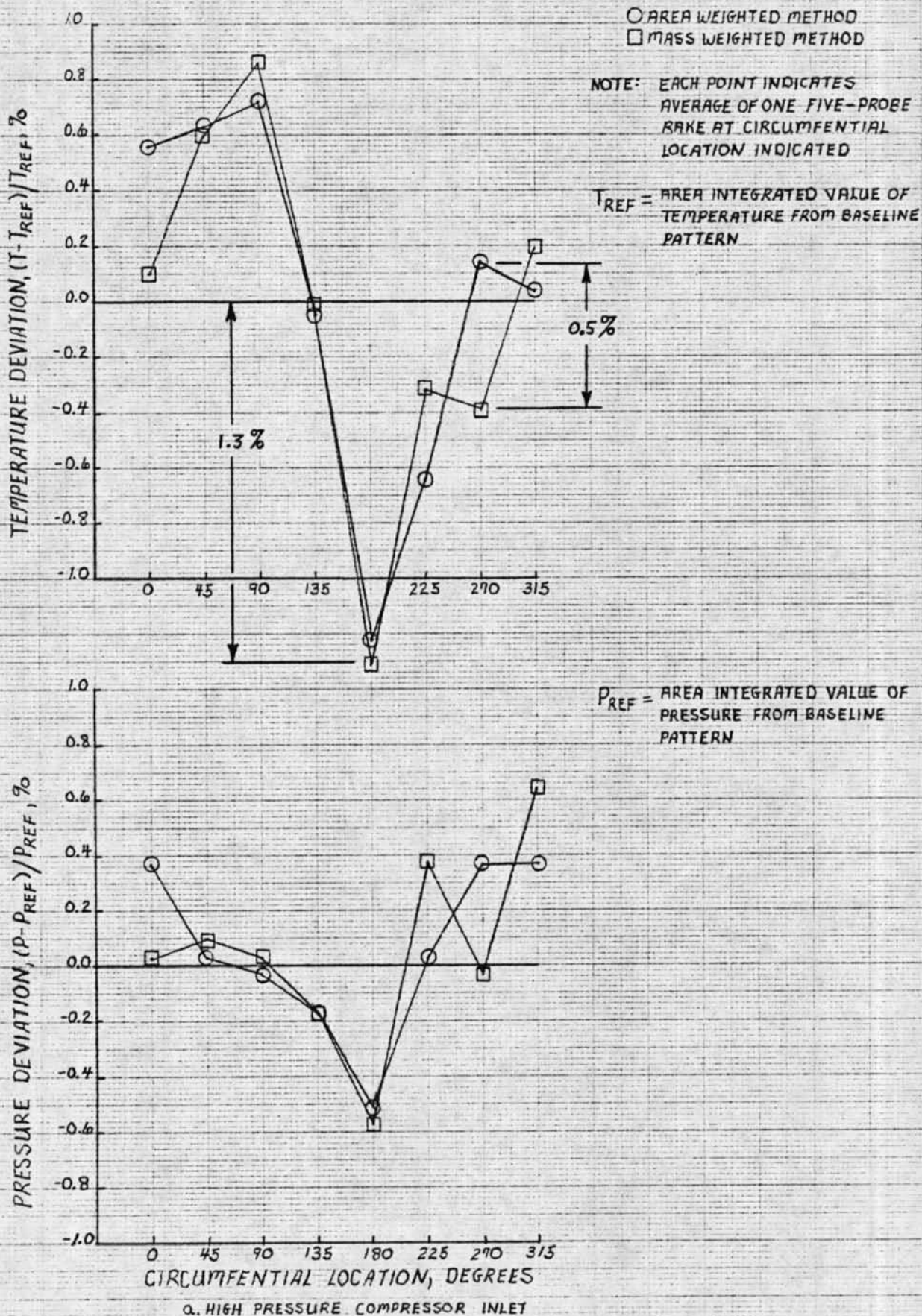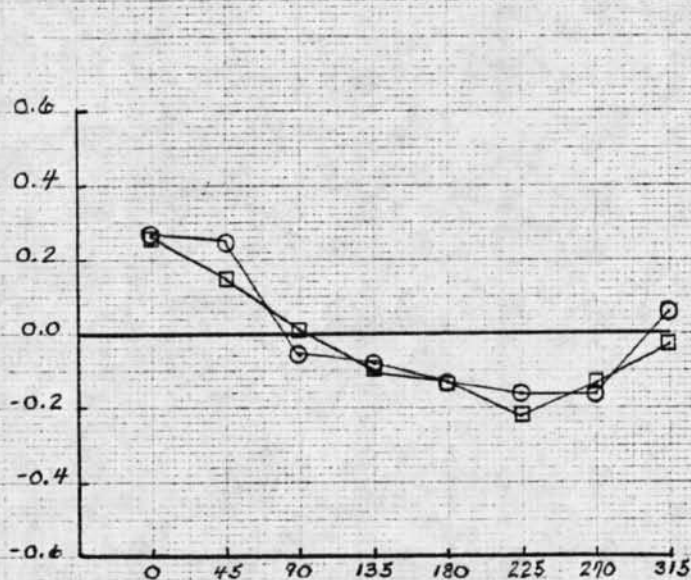Flow Averaging Evaluation

Figure 5. Comparison of Area Weighted and Mass Weighted
Averaging Methods for Baseline Pattern

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Figure 5.   Concluded

-21-
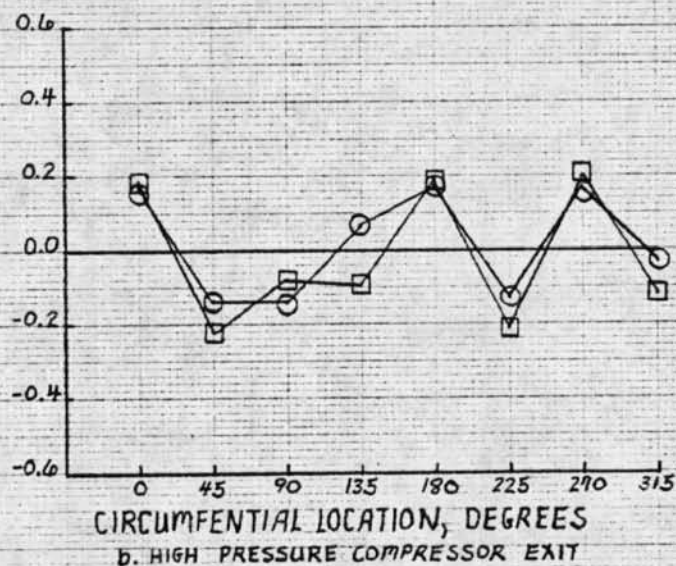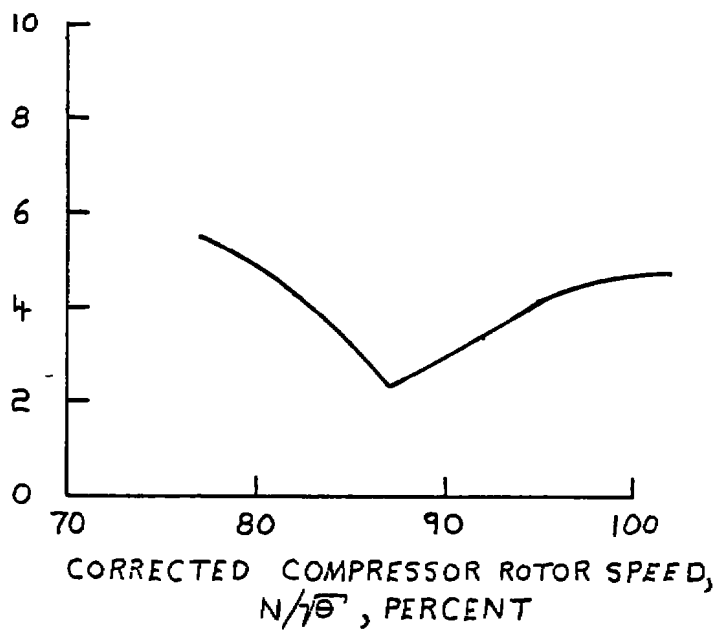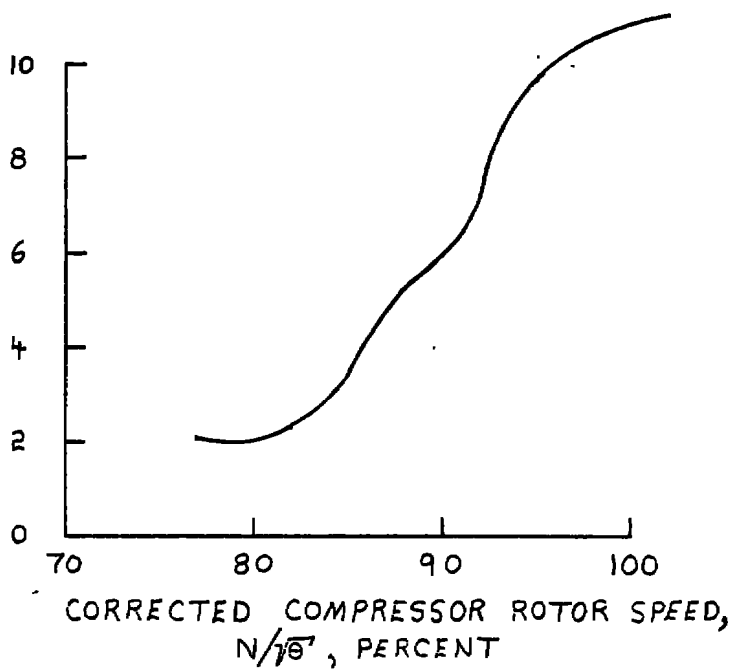
a. HIGH PRESSURE COMPRESSOR INLET

Figure 6. Distortion Index as a Function of Engine Power
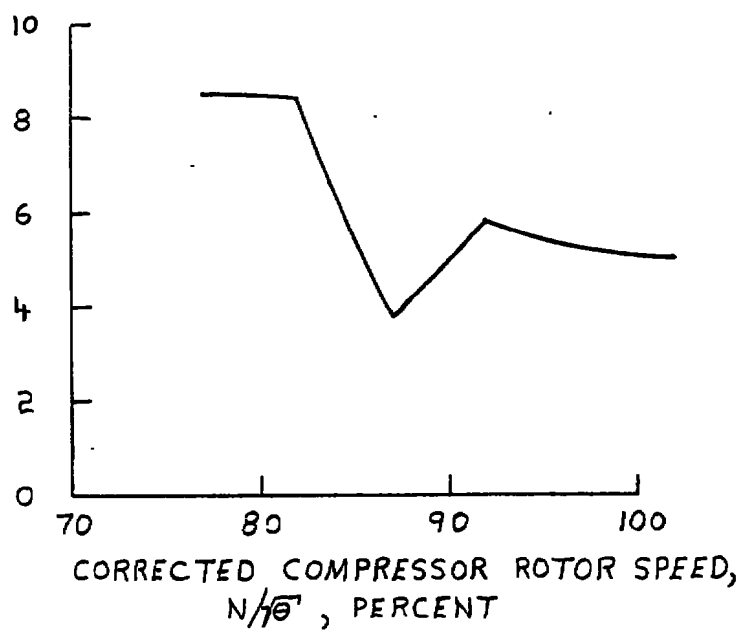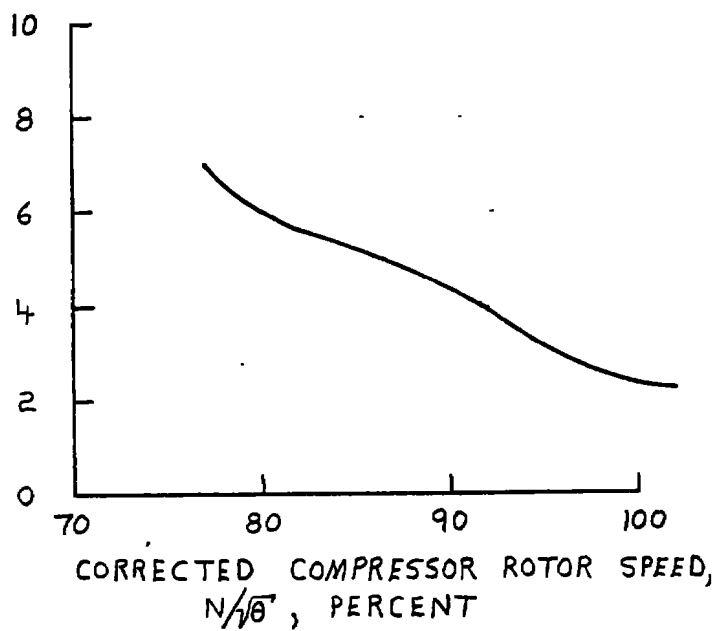
b. HIGH PRESSURE COMPRESSOR EXIT

Figure 6.   Concluded

Figure 7. Comparison of Flow Averaging Techniques

a. HIGH PRESSURE COMPRESSOR INLET

b. HIGH PRESSURE COMPRESSOR EXIT

Figure 7.   Concluded

TABLE 1
ENGINE SYSTEM FLOWPATH AVERAGING PRACTICES
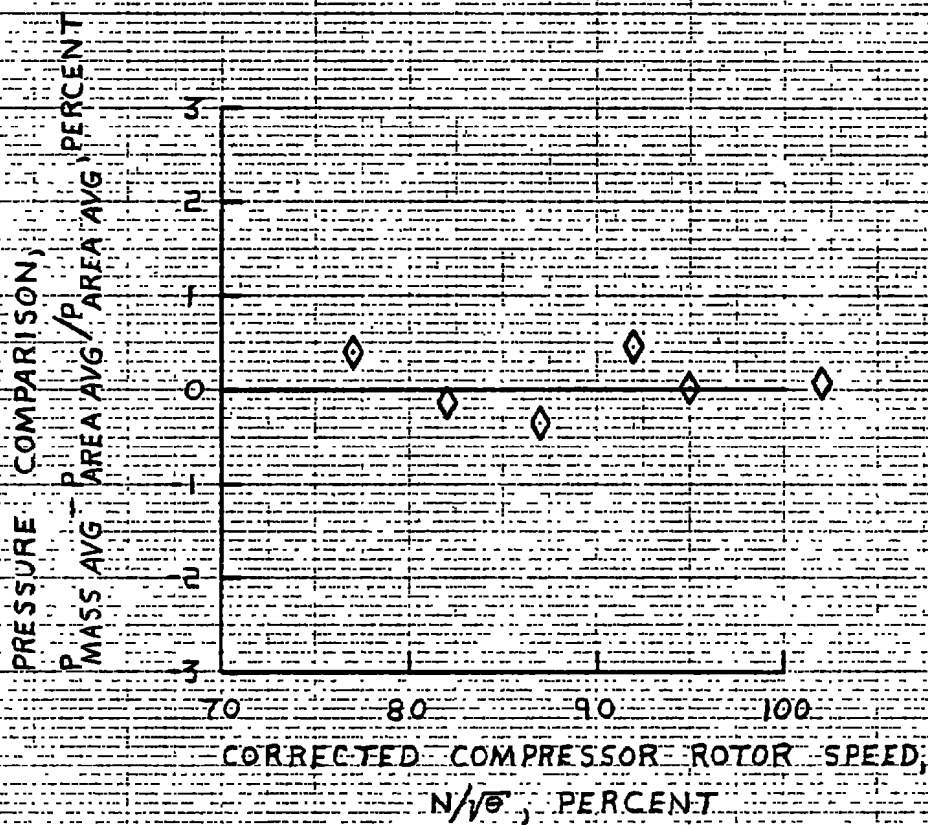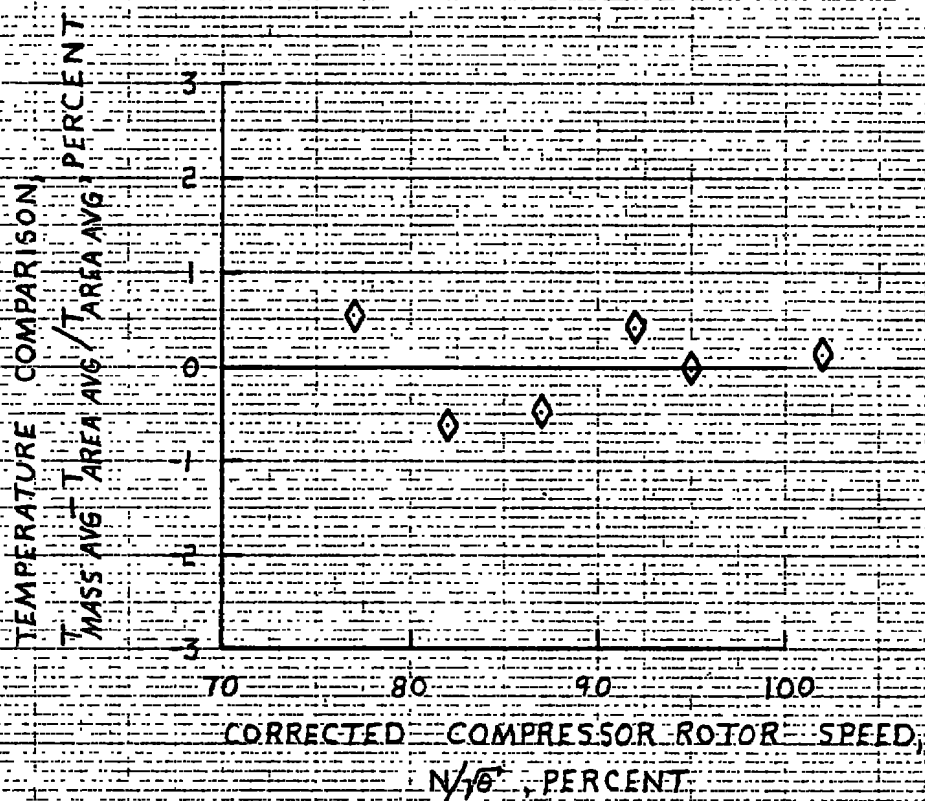
a. COMPRESSOR

ORGANIZATION	PERFORMANCE PARAMETERS	INLET PARAMETERS		OUTLET PARAMETERS	
		MEASURED	AVERAGED	MEASURED	AVERAGED
ARNOLD ENGINEERING DEVELOPMENT CENTER	Efficiency Pressure Ratio Temperature Ratio	P T PS (wall) Airflow	$\left.\begin{matrix}P_{AV}\\T_{AV}\end{matrix}\right\}$ Area AVG $PS_{AV}\}$ Numeric AVG	P T PS (wall)	$\left.\begin{matrix}P_{AV}\\T_{AV}\end{matrix}\right\}$ Area AVG $PS_{AV}\}$ Numeric AVG
CENTRE d'ESSAIS DES PROPULSEURS	Efficiency Pressure Ratio Temperature Ratio	P T Airflow	$P_{AV}\}$ Area AVG $T_{AV}\}$ Enthalpy Mass AVG	P T	$P_{AV}\}$ Area AVG $T_{AV}\}$ Enthalpy Mass AVG
NATIONAL GAS TURBINE ESTABLISHMENT	Efficiency Pressure Ratio Temperature Ratio	P T PS (wall) Airflow	$P_{AV}\}$ Area AVG $\left.\begin{matrix}T_{AV}\\PS_{AV}\end{matrix}\right\}$ Numeric AVG	P T PS (wall)	$P_{AV}\}$ Area AVG $\left.\begin{matrix}T_{AV}\\PS_{AV}\end{matrix}\right\}$ Numeric AVG
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (LEWIS RESEARCH CENTER)	Efficiency	P T Airflow	$\left.\begin{matrix}P_{AV}\\T_{AV}\end{matrix}\right\}$ Area AVG	P T	$\left.\begin{matrix}P_{AV}\\T_{AV}\end{matrix}\right\}$ Area AVG

TABLE I (CONTINUED)

b. COMBUSTOR

ORGANIZATION	PERFORMANCE PARAMETERS	INLET PARAMETERS		OUTLET PARAMETERS	
		MEASURED	AVERAGED	MEASURED	AVERAGED
ARNOLD ENGINEERING DEVELOPMENT CENTER	Efficiency Burner Loss	P T PS (wall) Airflow[d] Fuel Flow	$\left.\begin{array}{c}P_{AV}\\T_{AV}\end{array}\right\}$ Area AVG $\left.PS_{AV}\right\}$ Numeric AVG		P_{AV}^a H_{AV}^b $\left.T_{AV}\right\}$ $f(H_{AV}, P_{AV}, FAR)^c$
NATIONAL GAS TURBINE ESTABLISHMENT	Outlet Gas Temperature	P PS (wall) Airflow[d] Fuel Flow	$\left.P_{AV}\right\}$ Area AVG $\left.PS_{AV}\right\}$ Numeric AVG		P_{AV}^e T_{AV}^e
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (LEWIS RESEARCH CENTER)	Efficiency Burner Loss	P T Airflow[d] Fuel Flow	$\left.\begin{array}{c}P_{AV}\\T_{AV}\end{array}\right\}$ Area AVG		T_{AV}^c

[a] Burner Pressure is estimated using a numeric average of combustor chamber static pressure and estimated burner Mach number.

[b] Burner Enthalpy is estimated using compressor mass flow minus turbine cooling and leakage, compressor discharge enthalpy, measured fuel flow and combustion efficiency.

[c] Temperature obtained from thermodynamic tables for specified enthalpy, pressure and fuel-air ratio.

[d] Core flow is calculated using a high-pressure turbine flow function or from a compressor-turbine work balance.

[e] Calculated using airflow, fuel flow and combustion efficiency.

TABLE 1 (CONTINUED)

c. TURBINE

ORGANIZATION	PERFORMANCE PARAMETERS	INLET PARAMETERS		OUTLET PARAMETERS	
		MEASURED	AVERAGED	MEASURED	AVERAGED
ARNOLD ENGINEERING DEVELOPMENT CENTER	Efficiency H Pressure Ratio P Temperature Ratio L P	T P PS (wall)	P_{AV}^{a} H_{AV}^{b} T_{AV}} $f(H_{AV}, P_{AV}, FAR)^{c}$ T_{AV} P_{AV}} Area AVG PS_{AV}} Numeric AVG	T P PS (wall) T P	T_{AV} P_{AV}} Area AVG PS_{AV}} Numeric AVG T_{AV} P_{AV}} Area AVG
CENTRE d'ESSAIS DES PROPULSEURS	Efficiency Pressure Ratio Temperature Ratio	P T	P_{AV}} Area AVG T_{AV}} Enthalpy Mass AVG	P T	P_{AV}} Area AVG T_{AV}} Enthalpy Mass AVG

NATIONAL GAS TURBINE ESTABLISHMENT	Efficiency H
	Pressure Ratio P
	Temperature Ratio
	  L
	  P
		P
		T
		PS (wall)
			P_{AV}^{d}
			T_{AV}^{d}
			
			P_{AV}} Area AVG
			T_{AV}
			PS_{AV}} Numeric AVG
				P
				T
				PS (wall)
				
				P
				T
				PS (wall)
					P_{AV}} Area AVG
					T_{AV}
					PS_{AV}} Numeric AVG
					
					P_{AV}} Area AVG
					T_{AV}
					PS_{AV}} Numeric AVG

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (LEWIS RESEARCH CENTER)	Efficiency	P T	P_{AV} T_{AV}} Area AVG	P T	P_{AV} T_{AV}} Area AVG

[a] Burner Pressure is estimated using a numeric average of combustor chamber static pressure and estimated burner Mach number.

[b] Burner Enthalpy is estimated using compressor mass flow minus turbine cooling and leakage, compressor discharge enthalpy, measured fuel flow and combustion efficiency.

[c] Temperature obtained from thermodynamic tables for specified enthalpy, pressure and fuel-air ratio.

[d] Calculated using airflow, fuel flow and combustion efficiency.

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TABLE 1 (CONTINUED)

. d.   NOZZLE

ORGANIZATION	PERFORMANCE PARAMETERS	INLET PARAMETERS		OUTLET PARAMETERS	
		MEASURED	AVERAGED	MEASURED	AVERAGED
ARNOLD ENGINEERING DEVELOPMENT CENTER	Flow Coefficient Thrust Coefficient	P (no reheat)	P_{AV}} Area AVG $T_{AV}^{a,b,c}$	PS (atmos) Thrust	PS} Numeric AVG
NATIONAL GAS TURBINE ESTABLISHMENT	Flow Coefficient Thrust Coefficient	PS (wall)	PS_{AV}} Numeric AVG	PS(atmos.) Thrust	PS} Numeric AVG

$$^a T_{AV} = (VAE)^2/(2\gamma R/1-\gamma) \quad \left\{ 1 - \frac{P_{AV}(\text{reheat})}{PS_{AV}} \right.^{\frac{\gamma-1}{\gamma}} \left. \right\} \quad , \text{ then calculate thrust based on } T_{AV}; \text{ continue}$$

interation until set tolerance not exceeded.

^{b} Augmenter Energy Balance: (WAE) (HAE) = (WAI) (HAE) + WFA $\left(HFA + (\eta_A) (FHV) \right)$

^{c} Temperature obtained from thermodynamic tables for specified enthalpy, pressure and fuel-air ratio.

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TABLE 1 (CONCLUDED)

a. AUGMENTER

ORGANIZATION	PERFORMANCE PARAMETERS	INLET PARAMETERS		OUTLET PARAMETERS	
		MEASURED	AVERAGED	MEASURED	AVERAGED
ARNOLD ENGINEERING DEVELOPMENT CENTER	Efficiency $C_{O_{R_E}}$	P, T	P_{AV}, T_{AV} Area AVG	P (no reheat)	P_{AV} (no reheat) Area AVG, P_{AV} (reheat)[a], T_{AV}[b,c,d]
	Burner Loss $P_{A_{S_S}}^{BY-}$	P, T	P_{AV}, T_{AV} Area AVG		
	$M_{I_{X_{E_D}}}$	Fuel Flow	P_{AV}, H_{AV}[e], T_{AV} $f(P_{AV}, H_{AV}, FAR)$[d]		
NATIONAL GAS TURBINE ESTABLISHMENT	Efficiency $C_{O_{R_E}}$	P, T, PS (wall), Fuel Flow	P_{AV} Area AVG, T_{AV} Numeric AVG, PS_{AV}	P, T, PS (wall)	P_{AV}, T_{AV}[g,h], PS_{AV} Numeric AVG
	Outlet Gas $P_{A_{S_S}}^{BY-}$	P, T, PS (wall)	P_{AV} Area AVG, T_{AV} Numeric AVG, PS_{AV}		
	Temperature $M_{I_{X_{E_D}}}$	P, T	P_{AV}[i], T_{AV}		
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (LEWIS RESEARCH CENTER)	Efficiency	Airflow, Fuel Flow, T	T_{AV} Area AVG	P, Thrust	T_{AV}[j], P_{AV} Area AVG

a. P_{AV}(reheat) $= P_{AV}$(reheat) $\left[\left\{\dfrac{P_{AV}(reheat)}{P_{AV}(no\ reheat)}\right\}_{CALC} - \Delta P(drag)\right]$, where $\left\{\dfrac{P(reheat)}{P(no\ reheat)}\right\}_{CALC}$ is evaluated using Rayleigh line heat addition.

b. $T_{AV} = (VAE)^2/(2\,g\,R/1-\gamma)$ $\left\{1 - \dfrac{P_{AV}(reheat)}{PS_{AV}}^{\frac{\gamma-1}{\gamma}}\right\}$, then calculate thrust based on T_{AV}; continue interation until set tolerance not exceeded.

c. Augmenter Energy Balance: $(WAE)(HAE) = (WAI)(HAE) + WFA\left(HFA + (\eta_A)(FHV)\right)$

d. Temperature obtained from thermodynamic tables for specified enthalpy, pressure and fuel-air ratio.

e. $H_{AV} = \left\{(WAC)(HC) + (WAD)(HD)\right\}/WAT$

f. Calculated using static pressure and mass flow.

g. Calculated using thrust and mass flow.

h. Calculated using total pressure flow area and mass flow.

i. Calculated using airflow, fuel flow and combustion efficiency.

j. T_{AV} is calculated using measured thrust, exit total pressure, measured airflow and measured fuel flow.

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Table 2

ESTIMATED MEASUREMENT UNCERTAINTY

Parameter Designation	Precision Index	Bias	Uncertainty	
			Area Weighted	Mass Weighted
High-Pressure Compressor Inlet Temperature	±0.6°R	±0.9°R	±0.5°R	±2.7°R
High-Pressure Compressor Exit Temperature	±0.6°R	±0.25 percent of reading	±0.8°R	±2.5°R
High-Pressure Compressor Inlet Pressure	±0.15 percent of reading	±0.2 percent of reading	±0.02 psia	±0.14 psia
High-Pressure Compressor Exit Pressure	±0.15 percent of reading	±0.2 percent of reading	±0.12 psia	±0.14 psia

Table 3

EFFECT ON ENGINE PERFORMANCE OF A ONE PERCENT VARIATION OF TOTAL PRESSURE AND TEMPERATURE

	Engine Inlet		HPC Inlet		HPC Exit	
	P ±1%	T ±1%	P ±1%	T ±1%	P ±1%	T ±1%
Engine Net Thrust Change*	±0.80%	±0.40%	±0.04%	±0.05%	±1.00%	±0.04%
Specific Fuel Consumption Change**	±0.80%	±0.40%	±0.04%	±0.06%	±0.70%	±0.04%

$$* \quad \frac{FN_{DELTA} - FN_{NOMINAL}}{FN_{NOMINAL}} \quad x \quad 100$$

$$** \quad \frac{SFC_{DELTA} - SFC_{NOMINAL}}{SFC_{NOMINAL}} \quad x \quad 100$$

Derivation of expressions for mass-weighted method

$$P_{MASS\ AVG} = \frac{\Sigma\ P_i W_i}{W_{TOTAL_{meas}}}$$

where

$$W_i = \frac{\dot{m}_i \times PS_i \times A_i}{\sqrt{T_i}}$$

and

$$W_{TOTAL_{meas}} = \frac{\dot{m} \times PS_{AVG} \times A_{TOTAL}}{\sqrt{T_{MASS\ AVG}}}$$

and

$$PS_i = PS_{AVG}$$

Therefore,

$$P_{MASS\ AVG} = \frac{\Sigma\ P_i\ \dfrac{(\dot{m}_i \times PS_i \times A_i)}{\sqrt{T_i}}}{\dfrac{\dot{m} \times PS_{AVG} \times A_{TOTAL}}{\sqrt{T_{MASS\ AVG}}}}$$

For equal areas,

$$P_{MASS\ AVG} = \frac{PS_i \times A_i\ \Sigma\ P_i\ \dfrac{\dot{m}_i}{\sqrt{T_i}}}{PS_{AVG} \times nA_i\ \dfrac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}}$$

$$P_{MASS\ AVG} = \frac{\dfrac{1}{n}\ \Sigma\ P_i\ \dfrac{\dot{m}_i}{\sqrt{T_i}}}{\dfrac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}} \tag{1}$$

$$T_{MASS\ AVG} = \frac{\sum T_i W_i}{W_{TOTAL_{meas}}}$$

where W_i and $W_{TOTAL_{meas}}$ are the same as identified for $P_{MASS\ AVG}$ and

$$PS_i = PS_{AVG}$$

Therefore,

$$T_{MASS\ AVG} = \frac{\sum T_i \dfrac{(\dot{m}_i \times PS_i \times A_i)}{\sqrt{T_i}}}{\dfrac{\dot{m} \times PS_{AVG} \times A_{TOTAL}}{\sqrt{T_{MASS\ AVG}}}}$$

For equal areas,

$$T_{MASS\ AVG} = \frac{PS_i \times A_i \sum T_i \dfrac{\dot{m}_i}{\sqrt{T_i}}}{PS_{AVG} \times nA_i \dfrac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}}$$

$$T_{MASS\ AVG} = \frac{\dfrac{1}{n} \sum \dot{m}_i \sqrt{T_i}}{\dfrac{\dot{m}}{\sqrt{T_{MASS\ AVG}}}} \tag{2}$$

$$W_{TOTAL_{meas}} = \frac{\dot{m} \times PS_{AVG} \times A_{TOTAL}}{\sqrt{T_{MASS\ AVG}}} \tag{3}$$

The unknown values in expressions (1), (2), and (3) are

$P_{MASS\ AVG}$, $T_{MASS\ AVG}$, and PS_{AVG}.

An iterative solution of expressions (1), (2), and (3)

by assuming a value of PS_{AVG} determine the values of $P_{MASS\ AVG}$

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and $T_{MASS\ AVG}$. The proper assumption of PS_{AVG} is determined by

calculation of W_{TOTAL} and comparison to $W_{TOTAL_{meas}}$.